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(71) Applicant (*for all designated States except US*): INSTITUTE OF PHYSICS ACADEMY OF SCIENCES OF THE CZECH REPUBLIC [CZ/CZ]; Na Slovance 2, 180 40 Praha 8 (CZ).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): KADLEC, Stanislav [CZ/CZ]; Pod Lipkami 13, 150 00 Praha 5 (CZ). MUSIL, Jindřich [CZ/CZ]; Máchova 659, 252 30 Řvnice (CZ). RAJSKÝ, Antonín [CZ/CZ]; Konëvova 1728/118, 130 00 Praha 3 (CZ).

(74) Agent: TONINGEROVÁ, Daniela; Institute of Physics Academy of Sciences of the Czech Republic, Na Slovance 2, 180 40 Praha 8 (CZ).

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(57) Abstract

Method of magnetron sputtering, where a volume over the sputtered cathode surface is affected by a magnetic field and the field lines of the said magnetic field, which intersect the cathode surface twice, are spread on an area greater than 80 % of the total cathode surface area. The extinction pressure has a value greater than or equal to $1.5*10^{-2}$ Pa. Selected materials can be sputtered at the discharge power density of the cathode in the interval 2 to 250 W/cm^2 in a stable selfsputtering discharge, excited in the atmosphere of the sputtered atoms or in the mixture of the sputtered atoms with the working gas at pressures even lower than $1.5*10^{-2}$ Pa. Described are methods of discharge ignition and of adjustment of its characteristics by means of the magnetic field and other parameters. The method can be realized in a device for magnetron sputtering with a defined sputtered cathode surface consisting of an effective cathode area occupying at least 80 % of the total sputtered cathode surface, of a central cathode area and of a marginal cathode area. Various cathode shapes and magnetic field supplies are described.

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DESCRIPTION

Method and Device for Magnetron Sputtering

Technical Field

The invention concerns a method and a device for magnetron sputtering of materials and it solves the adjustment of discharge characteristics of the magnetron discharge, especially the excitation of a glow discharge at very low pressures, down to $1.5*10^{-2}$ Pa for any cathode material, and even at pressures lower than $1.5*10^{-2}$ Pa, down to the base pressure of the vacuum device, for selected cathode material in selfsputtering mode.

Prior Art

The cathodic sputtering in a d.c. glow discharge is a well-known process, utilized e.g. for deposition of thin films. The classical diode sputtering in a glow discharge between a cathode and an anode is not effective due to a low degree of gas ionization, enabling operation only at high working gas pressures, in the order of magnitude of 10 to 100 Pa. To achieve lower working pressure, various ways are used, the most usual of them being based on the magnetron principle, protected e.g. by the U.S. Pat. No. 3 878 085 (1975) and U.S. Pat. No. 4 166 018 (1979). In a planar magnetron, over the cathode, a magnetic field is generated in a form of a closed tunnel of field lines between two concentrically arranged poles and, as a result of the electron drift in crossed electric and magnetic field, the path of electrons gets considerably longer and their ionization ability is increased. When a voltage, usually about 500 to

1000 V, is led between the cathode and the vacuum chamber, at a pressure at least equal to an ignition pressure, usually between $5*10^{-1}$ Pa and 10 Pa, a stable glow discharge is excited and then a working pressure is set to a value greater than the extinction pressure, at which the discharge extinguishes spontaneously. The extinction pressures in magnetrons are usually in the range $2*10^{-1}$ to 1 Pa. Only as an exception, the magnetron glow discharge is stable at a working pressure less than about 10^{-1} Pa, the lower limit being about $5*10^{-2}$ Pa, according to J.L. Vossen and W. Kern (eds.), Thin Film Processes, Academic Press, New York, 1978. The reason for it is that a particular minimum density of molecules above the cathode is necessary for stable discharge excitation.

Besides the conventional balanced magnetron as described above, also unbalanced magnetrons have been developed, described e.g. in the papers B. Window and N.Savvides: Journal of Vacuum Science and Technology A 4, (1986) 196 and J. Musil, S. Kadlec a W.D. Münz: Journal of Vacuum Science and Technology A 9,(1991), 1171. The difference between the balanced and unbalanced magnetron consists in that in the case of the balanced magnetron the magnetic field at the cathode center is as strong as at the edge, whereas in the case of the unbalanced magnetron the field is either stronger in the center (unbalanced magnetron - type 1) or at the edge (unbalanced magnetron - type 2). In the unbalanced magnetron - type 2, the orientation of the magnetic field at the axis is reversed at a particular distance from the cathode, where the field of the outer pole predominates over the field of the inner pole. In practice, the name "unbalanced magnetron" is used for the unbalanced magnetron-type 2, because it exhibits higher plasma

density at the substrates as compared to both the balanced magnetron and unbalanced magnetron-type 1. All these magnetrons have rather similar magnetic field at the cathode vicinity, in the shape of a closed tunnel of field lines between two concentric poles, and therefore it is possible to call their magnetic field "a magnetic field of the magnetron type". Even at the unbalanced magnetrons, lower extinction pressure than at the conventional ones is not known. Also the values of the mean power density of the magnetron discharge at the cathode surface are normally in the order of magnitude of 1 to 20 W/cm^2 both in the conventional and the unbalanced magnetrons.

Extinction pressures values approximately $2*10^{-2}$ Pa to $3*10^{-2}$ Pa have been achieved at magnetron systems with special, exceptionally good plasma confinement at the magnetron cathode, using combinations of magnetic and electric fields. One of such systems is a combination of two circular magnetrons of the same size, placed against each other with oppositely oriented magnets, see M. Matsuoka, Y. Hoshi, and M. Naoe: Journal of Applied Physics, 60 (1986), 2096. Another method of achievement of low extinction pressures in magnetron sputtering, protected by the Czechoslovak patent application No. PV 4804-89, utilizes a combination of a magnetic field of a conventional or an unbalanced magnetron with a multipolar magnetic field.

A mechanism of confinement of a d.c. magnetron glow discharge, at pressures by orders of magnitude less than 10^{-2} Pa, has been published in the paper N. Hosokawa, T. Tsukada and H. Kitahara, Proc. of 8th International Vacuum Congress (Cannes, 1980), vol. 1. This glow discharge was observed at a magnet-

ron with a cylindrical cathode made of copper. The authors have shown that when the magnetron discharge is ignited at a common ignition pressure, in the order of magnitude 10^{-1} Pa, and after the power density at the cathode is increased over a particular minimum value, about 100 W/cm^2, the density of sputtered copper particles raises to such an extent that the discharge is sustained even after a reduction of the working pressure below 10^{-2} Pa. This discharge has been given the name "sustained selfsputtering discharge", because it is excited and sustained in a cloud of the sputtered material itself, which is being ionized in the discharge and it sputters back the cathode surface. Such a selfsputtering discharge then can be excited at very low pressures of the working gas, for example at the residual pressure of the vacuum device. For its stability, three conditions are essential:

1. High enough sputtering yield S;
2. High enough probability a of sputtered metal ionization;
3. High enough probability b of the ionized metal return back to the cathode.

To sustain a stable selfsputtering discharge, it is necessary to ensure that the following relation holds:

$$a.b.S > 1$$

The first condition is related to the choice of the cathode material and of the working discharge voltage. The second condition limits in practice the selfsputtering to high enough current and power density at the cathode, because the probability a is approximately directly proportional to the current density at the cathode. The quality of plasma confinement in the discharge is reflected in the combina-

tion of the second and third conditions. The fundamental question of the prior art in the selfsputtering discharge technology is finding the optimum way of plasma confinement.

Besides the above-mentioned cylindrical magnetron, a stable sustained selfsputtering discharge was achieved also in a conventional planar magnetron with a wide profile of the erosion zone, according to the invention of M. Geisler, J. Kieser and R. Kukla, DE 3527626 A1, see the paper: R. Kukla, T. Krug, R. Ludwig and K. Wilmers, Vacuum 41 (1990), 1968. Another successful experiment with the conventional planar magnetron has been made by W. Posadowski, Surface and Coatings Technology 49 (1991) 290. In all these cases, the experiments were successful only with a cathode made of copper, and the selfsputtering discharge on any other materials is not known.

To distinguish between the selfsputtering discharge and the conventional sputtering, the values of discharge power and working pressure of the used working gas are important. At pressures higher than the maximum selfsputtering pressure, practically unlimited reduction of the power fed into the discharge is possible, without spontaneous extinction of the discharge, compare Fig. 9. The discharge is thus excited in a gas with a high enough pressure and the sputtering is conventional. In the case of lower pressure values than the maximum selfsputtering pressure, there is always a minimum selfsputtering power, necessary for stable discharge excitation, where the minimum selfsputtering power corresponds to the working pressure. When the power fed into the discharge is reduced to a value lower than the minimum selfsputtering power, the discharge extinguishes. The minimum selfsputtering power increases when the working pressure

is decreased. When the power fed into the discharge is high enough, the working pressure can be reduced without any limit, compare Fig. 9. The region of working pressures lower than the maximum selfsputtering pressure and powers lower than the minimum selfsputtering power is thus a region of a stable selfsputtering discharge excitation. For example in the paper by W. Posadowski, Surface and Coatings Technology 49 (1991) 290, this region corresponded to the pressures below the maximum selfsputtering pressure - about $7*10^{-2}$ Pa in argon - and to the power density values at a copper cathode over 37 W/cm^2 at this pressure and over 67 W/cm^2 at the ultimate pressure of the vacuum device.

Disclosure of Invention

The drawbacks of the prior art and reaching as low working pressure as possible are solved by a method of magnetron sputtering according to the invention. The cathode to be sputtered is polarized with an a.c. radio-frequency or a d.c. negative voltage with respect to an anode and/or to a vacuum chamber, over the cathode is formed a magnetic field, comprising a closed tunnel of field lines above the cathode, then a stable glow discharge is excited between the cathode and the anode and/or the vacuum chamber at a pressure greater than or equal to an ignition pressure and then the working pressure of the working gas is adjusted to a value greater than an extinction pressure. The essence of the invention consists in that a volume over the sputtered cathode surface is affected by a magnetic field, the shape of which corresponds to the cathode shape. The field lines of the said magnetic field, which intersect the cathode surface twice, are spread on as large cathode area as

possible, in particular on an area greater than 80% of the total cathode surface area. The magnetic field lines, which intersect the cathode surface twice, are those, which emanate from the cathode closer to its center and intersect the cathode back farther from the center, or vice versa.

For some applications it is essential to ignite the discharge at as low pressure as possible. The ignition pressure can be adjusted for example in the range $3*10^{-2}$ Pa to 10^{-1} Pa, while the upper limit can be even higher and the lower limit depends for example on the size of the cathode and on the kind of the gas. In this range it is possible to minimize the ignition pressure with help of the voltage connected to the cathode. Its value can be e.g. higher than 200 V, while the minimum ignition pressure is usually reached in the range 500 V to 900 V.

For some other applications the goal is to reach stable sputtering at as low working pressure as possible after the discharge is ignited. The extinction pressure can be adjusted for example in the range $1.5*10^{-2}$ Pa to $5*10^{-2}$ Pa, while the upper limit can be even higher and the lower limit again depends for example on the size of the cathode and on the kind of the gas.

When the form of the magnetic field over the cathode is retained, it is still possible to adjust the magnetic field induction at the cathode surface. Thus it is possible first of all to adjust the minimum extinction pressure but also the ignition pressure and the discharge voltage and/or the discharge current. The induction in the middle of the field lines tunnel has then a value higher than 50 G, nevertheless the minimum extinction pressure is usually reached in the range 250 G to 1000 G.

The minimum extinction pressure can be also adjusted with help of the discharge current. Normally, the minimum extinction pressure is reached at lower values of the discharge current, except for very low current values, the optimum current density at the cathode being usually in the range 0.2 to 20 mA/cm^2.

The magnetic field over the sputtered cathode can be produced as a composition of at least two magnetic fields, namely of a magnetic field of magnetron type and of a disbalancing magnetic field. The discharge characteristics of the magnetron discharge are then adjusted by means of the shape and intensity of the resulting magnetic field, with help of varying the intensity of at least one of the two magnetic fields.

Another variant of method according to the invention consists in the ignition process of the selfsputtering discharge, involving three successive stages: In the first stage, a low pressure magnetron discharge is ignited between the cathode and the anode and/or the vacuum chamber with the magnetic field according to the basic method. In this stage, the pressure of the ignition gas can be adjusted in the interval $3*10^{-2}$ Pa to 100 Pa, and the negative d.c. voltage at the cathode with respect to an anode and/or to a vacuum chamber can be in the interval 300 V to 10 kV. Then, in the second stage, the power of the discharge is increased to a value at least equal to or higher than the value corresponding to the power load of the sputtered cathode, related to its entire area, in the range 2 to 250 W/cm^2, and, at the same time, to a value at least equal to or higher than the minimum selfsputtering power corresponding to the cathode material. Finally, in the third stage the working pressure of the chosen working gas is ad-

justed to a value lower than the maximum selfsputtering pressure and the discharge power is held on a value corresponding to or higher than the minimum selfsputtering power at the particular working pressure. The cathode material is thus sputtered in a stable selfsputtering discharge, excited in the atmosphere of the sputtered atoms or in the mixture of the sputtered atoms with the working gas. In this method, first during the second stage and not later than during the third stage, the volume over the sputtered cathode surface is affected by a magnetic field with unbalanced magnetron shape. Thus, in the third stage, all the parameters for the selfsputtering discharge excitation are adjusted.

In summary, this method utilizes extremely good plasma confinement by the magnetic field and thus it makes possible to introduce highest possible power into the discharge and to obtain high rate sputtering and selfsputtering.

The working pressure values in the third stage can be less than $1.5*10^{-2}$ Pa, that is lower than the pressure values utilized so far in the unbalanced magnetrons, and also less than the maximum selfsputtering pressure. The working gas can be the residual gas and the working pressure is then the residual gas pressure. The working gas can also be an inert gas, for example neon, argon, krypton or xenon, or a reactive gas, for example oxygen, nitrogen, carbon monoxide, carbohydrates and the like, or a mixture of such gases.

Another variant of the method according to the invention consist in that, first during the second stage and not later than during the third stage is adjusted the chosen intensity of the magnetic field of the magnetron type, used for selfsputtering, and

the intensity of the disbalancing magnetic field, used for selfsputtering, and the ratio of the intensity of the magnetic field of the magnetron type to the intensity of the disbalancing magnetic field, used for selfsputtering, is equal to or less than this ratio, used in the first ignition stage.

So, the most advantageous method of ignition of the selfsputtering discharge is to ignite it under the condititions optimized for the lowest ignition pressure and then, in the third stage of selfsputtering, the optimum magnetic field is either the same or more unbalanced.

A simple method is keeping both the intensity of the magnetic field of the magnetron type and the intensity of the disbalancing magnetic field, used for selfsputtering, identical to the intensities of these fields, used in the first ignition stage.

Another variant uses reduction of the intensity of the magnetic field of the magnetron type, used for selfsputtering, as compared to the intensity of the magnetic field of the magnetron type, used in the first ignition stage, while the intensity of the disbalancing magnetic field, used for selfsputtering, is identical with the intensity of the disbalancing magnetic field, used in the first ignition stage. Thus, it is possible to achieve adjustment of the minimum selfsputtering power and/or reduction of the minimum discharge current and/or increase of the discharge voltage, as compared to the values, achieved at the selfsputtering using the former method.

The method of sputtering according to the invention enables selfsputtering of many various materials. The material to be sputtered can be an element belonging to the group copper, silver, gold, or an alloy of at least two such elements. It can be also

a low melting point material of the group lead, cadmium, or an alloy of such elements.

Selfsputtering is also possible for copper alloys, such as various sorts of brass, that is alloy of copper with zinc and/or with led, where the zinc content is up to 50 weight percent and the led content is up to 10 weight percent.

The method also enables selfsputtering of some bronzes, especially aluminium, manganese and nickel based bronzes. In particular, these are alloys of copper with aluminium, nickel, manganese and iron, where the aluminium content is up to 11 weight percent, the sum of the aluminium and manganese contents is up to 16 weight percent, the nickel content is up to 5 weight percent, and the iron content is up to 2 weight percent. This material can thus be for example aluminium bronze, isabelin or novoconstantan.

The device for magnetron sputtering consists of a vacuum chamber equipped with a gas inlet and a gas outlet, of at least one planar cathode, the surface of which is made of a material to be sputtered, placed in the vacuum chamber, of a supply of an a.c. radio-frequency or a d.c. negative voltage, connected between the cathode and the vacuum chamber and/or between the cathode and a special anode, insulated from the vacuum chamber and placed in the vacuum chamber, and further of a cathode cooling circuit. The device is also equipped with a supply of a magnetic field, comprising a closed tunnel of field lines above the cathode. The essence of the invention consists in the definition of the spatial distribution of the magnetic field related to the shape and dimensions of the sputtered cathode. The sputtered cathode surface consists of an effective cathode area, limited by the field lines, which intersect the cathode

surface twice, of a central cathode area, situated inside and limited by the effective cathode area, and of the marginal cathode area, situated outside and limited by the effective cathode area. The effective cathode area according to the invention is as large as possible and it occupies at least 80% of the total sputtered cathode surface. At the same time, the central cathode area, or the marginal cathode area, or even both, can be zero.

A variant of the device describes a flexible layout, making possible to adjust the areas of the effective, central and marginal cathode areas in an optimal way for both low-pressure sputtering and selfsputtering. The essence of this variant is that the resulting magnetic field consists of the magnetic fields of at least two independent magnetic field supplies, namely of a supply of the magnetic field of the magnetron type, placed behind the cathode coaxially with the normal to the cathode surface at its center, and of a supply of the disbalancing magnetic field, placed behind the cathode coaxially with the normal to the cathode surface at its center, while at least one of both supplies is an electromagnet.

The next variants of the device utilize a simple magnetic circuit, placed for example behind the cathode and composed for example of permanent magnets or of one electromagnet.

The cathode can have a circular or nearly circular shape and then the central cathode area should occupy maximum 2% of the total sputtered cathode surface and the marginal cathode area maximum 20% of the total sputtered cathode surface, whereas the sum of both is not greater than 20%.

The cathode can also have an oblong shape, for example a rectangular or an oval shape, and then the central cathode area should occupy maximum 10% of the total sputtered cathode surface and the marginal cathode area maximum 15% of the total sputtered cathode surface, whereas the sum of both is not greater than 20%.

The above-mentioned relative limits of the areas are not sharp, and thus a weak effect, e.g. decrease of the extinction pressure, is reached even when these limits are exceeded slightly and, on the contrary, for reaching greatest effects the practical requirements must be even more strict.

Such strict requirements can be met in a device according to another variant, where the shape of the cathode is defined by the shape of the curve, which demarcates the effective area of the cathode. If for example the magnetic field exhibits axial symmetry, then the cathode has a circular shape. In the case of a magnetic field produced by a rectangular magnetic circuit, the cathode in general will not have rectangular shape, but a shape defined with the shape and dimensions of the effective cathode area, for example an oblong shape with rounded corners.

According to another variant of the device the cathode might have a rectangular shape but the margin of the cathode is covered with a shielding cover made of a conducting, non-magnetic material, which is electrically insulated from the cathode and the inner dimensions of which correspond to the dimensions of the effective area of the cathode. The shielding cover can be electrically connected to the anode or to the vacuum chamber or it can be kept on a selected potential, including the floating potential in the plasma. The discharge then is not excited in the spa-

ce between the shielding cover and the margin of the cathode and it is confined to the effective cathode area.

In the case when a basis of the magnetic field supply is identical with the magnetic field supply of a conventional magnetron, where the central cathode area occupies more than 10% of the total sputtered cathode area, a frame made of a magnetic soft material is placed above the outer edge of the cathode, electrically connected to the cathode, which attracts the field lines emanating from the cathode center and thus widens the effective cathode area.

In case of the device with two electromagnets, the supply of the magnetic field of the magnetron type can be a first coil, placed behind the cathode coaxially with the normal to the cathode surface at its center, connected to a first current supply, and inside the first coil a first core of a magnetic soft material can be placed. The supply of the disbalancing magnetic field can be a second coil with dimensions approximately equal to or greater than the cathode dimensions, placed behind the cathode coaxially with the normal to the cathode surface at its center, connected to a second current supply. Behind the cathode, around the first coil, a second core can be placed, with a ring shape, made of a magnetically conducting material. The second coil can be placed on the second core and the first core together with the second core can be magnetically connected behind the first coil with help of a plate made of a magnetically conducting material.

Brief Description of Drawings

The invention is described in more detail in 13 drawings.

Fig. 1 shows a schematic design of one possible embodiment of the device for magnetron sputtering according to the invention.

Fig. 2 shows a graph presenting the ignition pressure and the extinction pressure as functions of the ratio of currents I_2/I_1 in the device shown in Fig. 1.

Figs. 3, 4, and 5 show the shapes of field lines in one half of a cross-section in a circular magnetron, in a plane which contains the magnetron axis, and the figures correspond, respectively, to the points A, B, and C in Fig. 2 and to the values of the ratio I_2/I_1 : 1.25, 2.13, and 5.00.

Figs. 6.1 and 6.2 show, for a comparison, a cathode and the shape of the magnetic field of a magnetron according to the prior art, and also a design according to the invention, with a frame made of a soft magnetic material.

Fig. 7 shows a detail of the cathode, the shape of which is defined with the shape of the effective area.

Fig. 8 shows a detail of a cathode with a shielding cover.

Fig. 9 shows areas of stable excitation of the magnetron discharge as a function of the discharge power, including the distinction of the conventional sputtering and selfsputtering.

Figs. 10 and 11 show the characteristics of the selfsputtering discharge in the magnetron with a brass cathode. Fig. 10 shows minimum discharge current as a function of the intensity of the magnetic field of the magnetron type. Fig. 11, shows the mini-

mum power density as a function of the intensity of the disbalancing magnetic field.

Fig. 12 shows minimum argon pressure and discharge voltage as a function of the discharge current in a magnetron with cathode made of pure lead.

Detailed Description of the Invention - Examples of arrangement

Example 1

Fig. 1 shows a vacuum chamber 1 equipped with a gas inlet 2 and a gas outlet 3, in which an insulated planar circular cathode 4 is placed. A supply 5 of a d.c. negative voltage and current is connected between the cathode 4 and the vacuum chamber 1. The cooling circuit 6 enables flow of a cooling liquid. A magnetic field supply, comprising two electromagnets, is placed behind the cathode 4. The supply of the magnetic field of the magnetron type is a first coil 7, connected to a first current supply 8, and inside the first coil 7 is placed a first core 9 of a magnetic material. The supply of the disbalancing magnetic field is a second coil 11 with dimensions approximately equal to the cathode dimensions, connected to a second current supply 12. Behind the cathode 4, around the first coil 7 but inside the second coil 11, a second core 13 is placed, with a ring shape, made of a magnetically soft material. The first core 9 together with the second core 13 are magnetically connected behind the first coil 7 with help of a plate 14 made of a magnetically conducting material. In this example the relationship of the cathode 4 dimensions and the magnetic field shape is such that the effective cathode area 15, defined by the field lines 301,302 comprises almost entire cathode sur8

face, the central cathode area 16 occupies only about 0.05% of the total sputtered cathode 4 surface and the marginal cathode area is missing. The field line 302 delimits the effective cathode area 15. The central cathode area 16, the marginal cathode area, and the effective cathode area 15 can be adjusted with help of the ratio of currents I_2/I_1, where I_1 is the current from the first current supply 8 to the first coil 7 and I_2 is the current from the second current supply 12 to the second coil 11.

Example 2

Fig. 2 shows a graph of the ignition pressure and of the extinction pressure as functions of the ratio of the intensity of the disbalancing magnetic field to the intensity of the magnetic field of the magnetron type in the device shown in Fig. 1 with a circular cathode with diameter 124 mm, made of brass. Its approximate composition was 58 weight percent of copper, 40 weight percent of zinc and 2 weight percent of lead. The working gas was argon. The discharge current was 1 A and the ignition voltage was 1000 V. The ratio of currents I_2/I_1 is a measure of the ratio of both magnetic fields, where I_1 is the current from the first current supply 8 to the first coil 7 and I_2 is the current from the second current supply 12 to the second coil 11. The curve 201 shows the ignition pressure and the curve 202 the extinction pressure as functions of the ratio I_2/I_1. Both curves 201 and 202 exhibit a pronounced minimum, labelled B, corresponding to the ratio I_2/I_1=2.13. This ratio corresponds to the magnetic field shape, given in Fig. 4. The point A corresponds to the ratio I_2/I_1=1.25 and to the magnetic field shape given in Fig. 3, and the point C corresponds to the ratio

$I_2/I_1=5.0$ and to the magnetic field shape, given in Fig. 5. Figs. 3, 4, and 5 show the shapes of field lines in one half of a cross-section in the circular magnetron in a plane which contains the magnetron axis. The field lines 301 intersect the cathode surface 4 twice and the field line 302 is the most distant of such field lines. The intersections of the field lines 302 with the cathode surface 4 thus delimit the effective cathode area 15. The field lines 303 in Fig. 3 emanate from the central cathode area 16 and do not intersect the cathode 4 twice but they intersect for example the vacuum chamber 1 outside the cathode 4. Analogously, the field lines 304 in Fig. 5 emanate from the marginal cathode area 17 and do not intersect the cathode 4 twice. In Fig. 4, the central cathode area 16 and the marginal cathode area 17 almost do not exist and the field lines 302 just connect the central point of the cathode 4 with its edge. The effective cathode area 15 thus occupies practically the entire sputtered cathode surface 4 and, just in this arrangement, one reaches the best plasma confinement at the magnetron cathode 4 as well as the minimum ignition and extinction pressures.

Example 3

Identical conclusions about the inter-relationship between the magnetic field shape above the cathode and the minimum ignition and extinction pressures, like in Example 2, were gained in a magnetron with a circular cathode with diameter 100 mm made of copper, and also with another cathode made of titanium.

Example 4

In the same arrangement as in Example 1, at the ratio $I_2/I_1=2.13$, the ignition pressures were measured as a function of the voltage led to the cathode to ignite the discharge, in the range 400 V to 1000 V. The ignition pressures was in the range $3*10^{-2}$ Pa to $8*10^{-2}$ Pa, while the minimum was found in the range 700 V to 750 V.

Example 5

In the same arrangement as in Example 1, at the ratio $I_2/I_1=2.0$ and at the discharge current 175 mA, the extinction pressures were measured as a function of the magnetic field induction at the cathode surface in the center of the field line tunnel in the range of values between 160 G and 600 G . The extinction pressure was in the range $1.5*10^{-2}$ Pa to $2.3*10^{-2}$ Pa, while the minimum was found at the magnetic field induction of approximately 400 G. Comparison of this example with example 2 shows that the magnetic field shape and the effective cathode area exhibit more pronounced effect on the extinction pressure values than the magnetic field induction.

Example 6

In the same arrangement as in Example 1, at the ratio $I_2/I_1=2.13$, the extinction pressures were measured as a function of the discharge current in the range 50 mA to 3 A. The extinction pressure was in the range $1.5*10^{-2}$ Pa to $3*10^{-2}$ Pa, while the minimum was found at the discharge current about 175 mA. This corresponds to a discharge current density about 1.5 mA/cm^2.

Example 7

Another example of the device according to the invention is shown in Figs. 6.1 and 6.2.

Fig. 6.1 shows schematically, in a cross-section, the cathode 4 and the magnetic circuit 602 of a conventional magnetron according to the prior art.

Fig. 6.2 shows an example of the device according to the invention, where, compared to Fig. 6.1, a frame 601 made of a soft magnetic material is added above the outer edge of the cathode 4 and the frame is electrically connected to the cathode 4. The frame 601 attracts very effectively the magnetic field lines, thus widening the effective cathode area 15 and making better magnetic field confinement above the sputtered cathode 4. This design results in a significant reduction of the extinction pressure.

It has been found experimentally that while the conventional magnetron with a Ti cathode with diameter 100 mm exhibits minimum extinction pressure 8.2×10^{-2} Pa at the discharge current 0.5 A, the extinction pressure of the same magnetron, with the frame 601 added, is reduced down to only 4.3×10^{-2} Pa, i.e. to about one half. Another advantage is that the coil current necessary for the extinction pressure minimum dropped from 1.4 A down to 0.9 A in case of using the Fe frame 601.

Example 8

Fig. 7 shows an example of the design, where the magnetic field is produced by a rectangular magnetic circuit 701. The field lines 302 demarcate the edges of the effective cathode area 15. The shape of the cathode 4 is defined by the outer edge of the effective cathode area 15, it has thus an oblong shape with rounded corners. Therefore the marginal cathode

area is eliminated and only a small central cathode area 16 remains.

Example 9

Fig. 8 shows, in a cross-section, the cathode 4 with the magnetic circuit 801. The margin of the cathode 4 is covered with a shielding cover 802, the inner dimensions of which are defined by the outer edge of the effective cathode area 15. The shielding cover 802 is made of a conducting, non-magnetic material and it is electrically insulated from the cathode 4. The shielding cover 802 is mechanically fixed to the vacuum chamber 1 via the insulation 803. So, it is kept on the floating potential. It also can form the discharge anode or be electrically connected to the vacuum chamber. The discharge then is not excited in the space between the shielding cover 802 and the margin of the cathode 4 and it is confined to the effective cathode area 15. Therefore, in this design, it is not important how large is the marginal cathode area, covered with the shielding cover 802.

Example 10

Figs. 10 and 11 show the characteristics of the selfsputtering discharge in a magnetron, described in Fig.1 and in example 1, having circular cathode with diameter 124 mm, made of brass. In this case, the working gas in the third stage was the residual gas and the working pressure was the residual gas pressure of about $2*10^{-3}$ Pa. Fig.10 shows, how the minimum discharge current depends on the current I_1, that is on the intensity of the magnetic field of the magnetron type. The current I_2 is here a parameter of the curves. The points, marked by small circles, label the ratio $I_2/I_1=2.13$, when minimum ignition pressure

is achieved in the first stage of discharge ignition. Fig.10 illustrates how it is possible to reduce the minimum discharge with help of reduction of the intensity of the magnetic field of the magnetron type by the reduction of the current I_1. It is also evident that provided the ratio of currents I_2/I_1 is kept higher than 2.13, then the magnetron discharge current is adjusted especially with help of the intensity of the magnetic field of the magnetron type, or of the current I_1. In contrast, provided the ratio of currents I_2/I_1 is less than 2.13, then the minimum discharge current begins to increase sharply.

Fig.11 shows, how the minimum power density can be adjusted with help of adjustment of the current I_2, or of the intensity of the disbalancing magnetic field. The current I_1 is here a parameter of the curves. The points, marked by small circles, label again the ratio $I_2/I_1=2.13$. Fig. 11 again illustrates that provided the ratio of currents I_2/I_1 is kept higher than 2.13, then the minimum power density in selfsputtering is approximately constant. These values are lower for each curve with a constant value I_1 than if the current I_2 gets lower than approximately $2.13 * I_1$.

Optimum regime of selfsputtering discharge ignition has been achieved for example using the following procedure: The magnetron discharge was ignited in argon at a pressure $4*10^{-2}$ Pa and at the currents $I_1 = 2$ A, $I_2 = 4$ A, that is at $I_2/I_1 = 2$. Thus, in the first stage of discharge ignition, the ratio of the intensity of the magnetic field of the magnetron type to the intensity of the disbalancing magnetic field was used, at which the field lines of the resulting magnetic field occupy an area greater than 80% of the total cathode surface area. In the second

stage, at an argon pressure $4*10^{-2}$ Pa, the power of the glow discharge was increased from the value 0.1 kW up to 4.4 kW, then the current I_1 was reduced for example down to 1 A, that is to $I_2/I_1 = 4$. Thus, in this case, the ratio of the intensity of the magnetic field of the magnetron type to the intensity of the disbalancing magnetic field, used for selfsputtering, is less than this ratio, used in the first ignition stage. In the third stage, the working pressure of the working gas was adjusted to the residual pressure of $2 * 10^{-3}$ Pa and at these conditions, a stable sustained selfsputtering discharge was operated at power values of 4.1 kW and higher. This is lower value than what would be achieved provided identical magnetic field were kept as in the first stage of discharge ignition.

Example 11

In a circular planar magnetron having cathode with diameter 124 mm, made of pure copper, qualitatively very similar results as in example 10 were achieved, especially in dependence on the intensity of the magnetic field of the magnetron type and on the intensity of the disbalancing magnetic field. Selfsputtering in the residual gas atmosphere at pressure $2*10^{-3}$ Pa was achieved at minimum discharge current values down to 9.8 A and at discharge voltage values from 585 V to 750 V. At the current $I_1 = 1.0$ A and $I_2 = 4$ A, a stable selfsputtering discharge with a copper cathode was achieved at minimum power density of only 56.7 W/cm². This is significantly lower value than the lowest power density published so far with a conventional magnetron, namely 67 W/cm².

Example 12

When a similar circular planar magnetron as in example 1 was used, but with a cathode with diameter 100 mm, made of pure silver, selfsputtering in the residual gas atmosphere at pressure $2*10^{-3}$ Pa was achieved at minimum discharge current about 3 A and at discharge voltage about 760 V, that is at power density about 29 W/cm^2.

Example 13

In a circular planar magnetron as in example 12, having a cathode with diameter 100 mm, made of pure lead, the extinction argon pressure and discharge voltage were measured as functions of the minimum discharge current, and the results achieved are shown in Fig. 12. A stable selfsputtering discharge was observed in a mixture of the sputtered lead atoms with argon gas, at argon pressures lower than about $2.3*10^{-2}$ Pa, and at minimum discharge current value between 0.4 A and 0.75 A. This corresponds to achievement of selfsputtering discharge at minimum power density between 2.4 and 6.6 W/cm^2. When the magnetic field was optimised, minimum power density 2.1 W/cm^2 was achieved with this cathode at argon pressure $2.2*10^{-2}$ Pa and minimum power density 4.9 W/cm^2 at pressure $2.3*10^{-3}$ Pa.

Example 14

In a similar experiment as in example 13 but with a cathode made of pure cadmium, selfsputtering discharge was achieved at argon pressure lower than about $2*10^{-2}$ Pa and at minimum discharge current between 0.8 and 1.5 A.

Example 15

Another measurement was made in a circular planar magnetron as in example 12, with a cathode with diameter 100 mm, made of aluminium bronze with the following composition: 9 weight percent of aluminium, 4 weight percent of nickel, 1.2 weight percent of manganese and 1 weight percent of iron, where the rest was copper. Stable selfsputtering discharge was achieved, even in the residual gas atmosphere at pressure about $2*10^{-3}$ Pa. The minimum power density was 77 W/cm^2. The method according to the invention thus enables even selfsputtering of alloys, containing an element which does not allow selfsputtering in its pure form. The concentration of this element must not exceed a particular limit, which depends on the alloy components.

Industrial Applicability

The invention can be utilized especially for the ignition and maintaining of a magnetron discharge at low pressures, down to the values of about $1.5*10^{-2}$ Pa and of a selfsputtering discharge at pressures in the order of magnitude from $5*10^{-2}$ Pa down to the residual pressure of the vacuum device. Such magnetron discharges feature the advantage of wider ranges of operation parameters compared to conventional magnetron sputtering. When used for thin film deposition, it reduces the film contamination by the gas species, enables a wider ranges of deposited film parameters, reduces the collision probability of the sputtered atoms with the gas, thus reducing their thermallization and enabling straight-line movement of particles.

The advantage of the selfsputtering discharge consists in high values of applied power and thus in high sputtering rates. Moreover, a large fraction of the sputtered atoms is ionized.

The method according to the invention is applicable for the film deposition for the so-called lift-off technology, covering of step-like structures with a high ratio of the step height to the step width, or hole filling for holes with a high depth/diameter ratio and the like. It can for example exclude or suppress contamination of the films by gas, it minimizes the probability of collisions of the sputtered atoms with the gas, thus eliminating their thermallization and it enables straight-line movement of particles. The application of the invention is, however, not necessarily restricted just to the thin film deposition but it can be used for example for low pressure etching.

(End of Description)

CLAIMS

1) A method of magnetron sputtering, where the cathode to be sputtered is polarized with an a.c. radio-frequency or a d.c. negative voltage with respect to an anode and/or to a vacuum chamber, over the cathode is formed a magnetic field, comprising a closed tunnel of field lines above the cathode, then a stable glow discharge is excited between the cathode and the anode and/or the vacuum chamber at a pressure greater than or equal to an ignition pressure and then the working pressure of the working gas is adjusted to a value greater than an extinction pressure, characterized in that a volume over the sputtered cathode surface is affected by a magnetic field and the field lines of the said magnetic field, which intersect the cathode surface twice, are spread on an area greater than 80% of the total cathode surface area.

2) A method in accordance with claim 1, characterized in that the ignition pressure has a value greater than or equal to $3*10^{-2}$ Pa.

3) A method in accordance with claim 1, characterized in that the extinction pressure has a value greater than or equal to $1.5*10^{-2}$ Pa.

4) A method in accordance with claim 2, characterized in that the minimum ignition pressure is adjusted with help of the voltage connected to the cathode.

5) A method in accordance with claim 3, characterized in that the minimum extinction pressure is

adjusted with help of the magnetic field induction at the cathode surface.

6) A method in accordance with claim 3, characterised in that the minimum extinction pressure is adjusted with help of the discharge current.

7) A method in accordance with claim 1, characterized in that the magnetic field over the sputtered cathode is produced by composition of at least two magnetic fields, namely of a magnetic field of magnetron type and of a disbalancing magnetic field, while the discharge characteristics of the magnetron discharge are adjusted by means of the shape and intensity of the resulting magnetic field with help of varying the intensity of at least one of the two magnetic fields.

8) A method in accordance with claim 1, characterised in that the ignition process of the selfsputtering discharge consists of three successive stages, where in the first stage a low pressure magnetron discharge is ignited between the cathode and the anode and/or the vacuum chamber with the magnetic field according to claim 1, in the second stage the power of the discharge is increased to a value at least equal to or higher than the value corresponding to the power load of the sputtered cathode, related to its entire area, in the range 2 to 250 W/cm^2, and to a value at least equal to or higher than the minimum selfsputtering power corresponding to the cathode material, and in the third stage the working pressure of the chosen working gas is adjusted to a value lower than the maximum selfsputtering pressure and the discharge power is held on a value corresponding

to or higher than the minimum selfsputtering power at the particular working pressure and the cathode material is sputtered in a stable selfsputtering discharge, excited in the atmosphere of the sputtered atoms or in the mixture of the sputtered atoms with the working gas, while, first during the second stage and not later than during the third stage, the volume over the sputtered cathode surface is affected by a magnetic field with unbalanced magnetron shape.

9) A method in accordance with claim 8, characterized in that the working pressure of the working gas in the third stage has a value lower than $1.5*10^{-2}$ Pa.

10) A method in accordance with claim 7 and 8, characterized in that first during the second stage and not later than during the third stage is adjusted the chosen intensity of the magnetic field of the magnetron type, used for selfsputtering, and the intensity of the disbalancing magnetic field, used for selfsputtering, and the ratio of the intensity of the magnetic field of the magnetron type to the intensity of the disbalancing magnetic field used for selfsputtering is equal to or less than this ratio, used in the first ignition stage.

11) A method in accordance with claim 10, characterized in that both the intensity of the magnetic field of the magnetron type and the intensity of the disbalancing magnetic field, used for selfsputtering, are identical to the intensities of these fields, used in the first ignition stage.

12) A method in accordance with claim 10, characterised in that the adjustment of the minimum selfsputtering power and/or reduction of the minimum discharge current and/or increase of the discharge voltage, as compared to the values achieved at the selfsputtering in the method in accordance with claim 11, is achieved by means of a reduction of the intensity of the magnetic field of the magnetron type, used for selfsputtering, as compared to the intensity of the magnetic field of the magnetron type, used in the first ignition stage, while the intensity of the disbalancing magnetic field, used for selfsputtering, is identical with the intensity of the disbalancing magnetic field, used in the first ignition stage.

13) A method in accordance with claim 8, characterised in that the material to be sputtered is an element belonging to the group copper, silver, gold, or an alloy of at least two such elements.

14) A method in accordance with claim 8, characterised in that the material to be sputtered is an element belonging to the group lead, cadmium, or an alloy of such elements.

15) A method in accordance with claim 8, characterised in that the material to be sputtered is an alloy of copper with zinc and/or with lead, where the zinc content is up to 50 weight percent and the lead content is up to 10 weight percent.

16) A method in accordance with claim 8, characterised in that the material to be sputtered is an alloy of copper with aluminium, nickel, manganese and iron, where the aluminium content is up to 11 weight

percent, the sum of the aluminium and manganese contents is up to 16 weight percent, the nickel content is up to 5 weight percent, and the iron content is up to 2 weight percent.

17) A device for magnetron sputtering to perform the method in accordance with claim 1 and 8, consisting of a vacuum chamber equipped with a gas inlet and a gas outlet, of at least one planar cathode, the surface of which is made of a material to be sputtered, placed in the vacuum chamber and equipped with a cooling circuit, of a supply of an a.c. radio-frequency or a d.c. negative voltage, connected between the cathode and the vacuum chamber and/or between the cathode and a special anode, insulated from the vacuum chamber and placed in the vacuum chamber, and the device is further equipped with a supply of a magnetic field, comprising a closed tunnel of field lines above the cathode, characterized in that the sputtered cathode surface (4) consists of an effective cathode area (15), limited by the field lines (301,302), which intersect the cathode surface twice, of a central cathode area (16), situated inside and limited by the effective cathode area (15), and of the marginal cathode area (17), situated outside and limited by the effective cathode area (15), while the effective cathode area (15) occupies at least 80% of the total sputtered cathode surface (4).

18) A device in accordance with claim 17 to perform the method in accordance with claim 7, characterized in that the magnetic field supply consists of at least two independent magnetic field supplies, namely of a supply of the magnetic field of the mag-

netron type, placed behind the cathode coaxially with the normal to the cathode surface at its center, and of a supply of the disbalancing magnetic field, placed behind the cathode coaxially with the normal to the cathode surface at its center, while at least one of both supplies is an electromagnet.

19) A device in accordance with claim 17 characterized in that the cathode (4) has a circular shape and that the central cathode area (16) occupies maximum 2% of the total sputtered cathode surface (4) and the marginal cathode area (17) occupies maximum 20% of the total sputtered cathode surface (4), whereas the sum of both is not greater than 20%.

20) A device in accordance with claim 17, characterized in that the cathode (4) has an oblong shape, for example a rectangular or an oval shape, and that the central cathode area (16), occupies maximum 10% of the total sputtered cathode surface (4) and the marginal cathode area (17) occupies maximum 15% of the total sputtered cathode surface (4), whereas the sum of both is not greater than 20%.

21) A device in accordance with claim 17, characterized in that the shape of the cathode (4) is defined by the shape of the curve, which demarcates the effective area (15) of the cathode (4).

22) A device in accordance with claim 17, characterized in that the margin of the cathode (4) is covered with a shielding cover (802) made of a conducting, non-magnetic material, which is electrically insulated from the cathode (4) and the inner dimensi-

ons of which correspond to the dimensions of the effective area (15) of the cathode (4).

23) A device in accordance with claim 17, characterized in that a frame (601) made of a magnetic soft material is placed above the outer edge of the cathode (4) and the frame is electrically connected to the cathode (4).

24) A device in accordance with claim 18, characterized in that the supply of the magnetic field of the magnetron type is a first coil (7), placed behind the cathode (4) coaxially with the normal to the cathode (4) surface at its center, connected to a first current supply (8), and inside the first coil (7), a first core (9) of a magnetic material is placed, behind the cathode (4) around the first coil (7) a second core (13) is placed, with a ring shape and made of a magnetically conducting material, the supply of the disbalancing magnetic field is a second coil (11) with dimensions approximately equal to or greater than the cathode (4) dimensions, placed behind the cathode coaxially with the normal to the cathode (4) surface at its center, connected to a second current supply (12), placed on the second core (13), and the first core (9) together with the second core (13) are magnetically connected behind the first coil (7) with help of a plate (14) made of a magnetically conducting material.

(End of Claims)

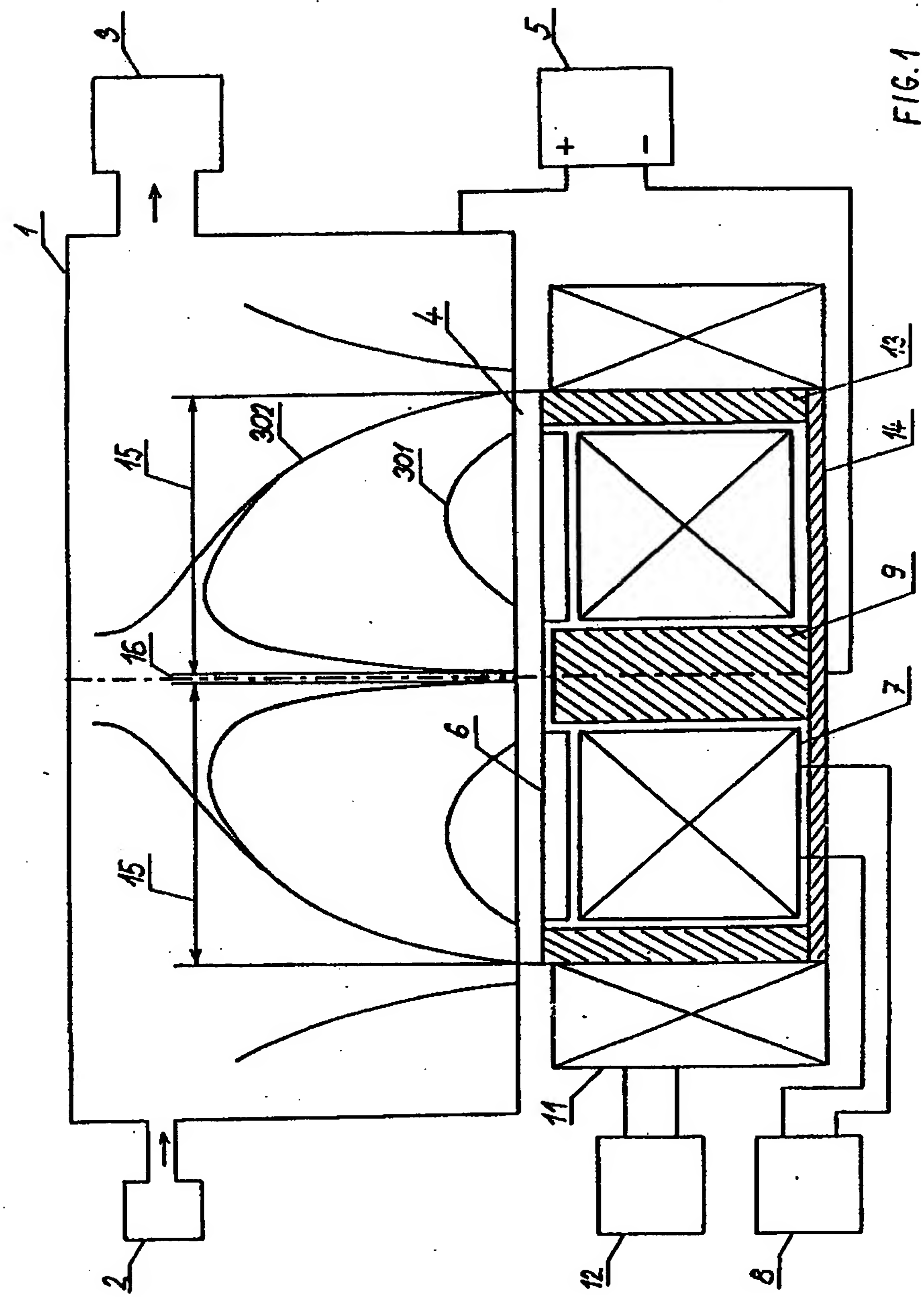
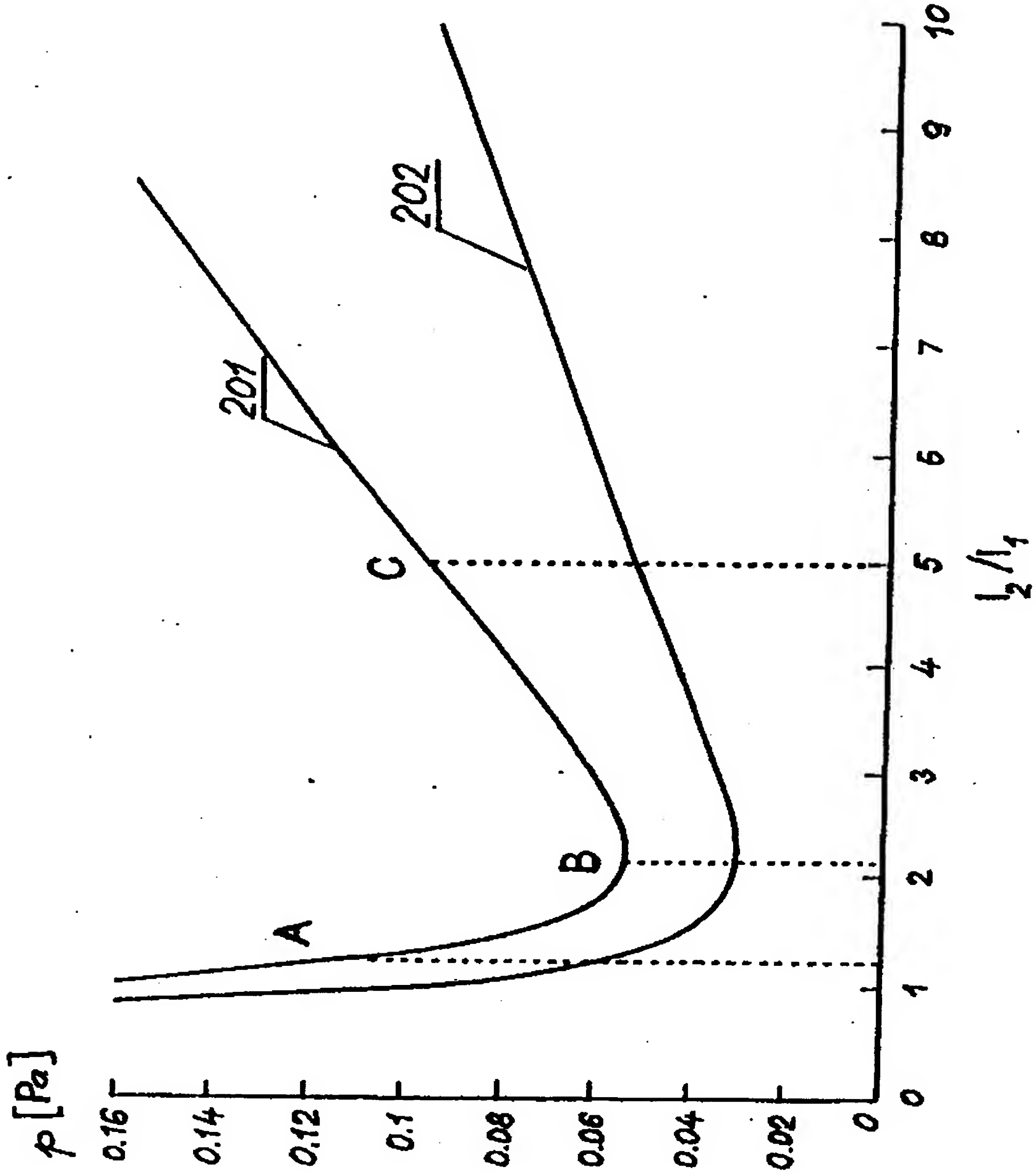


FIG. 1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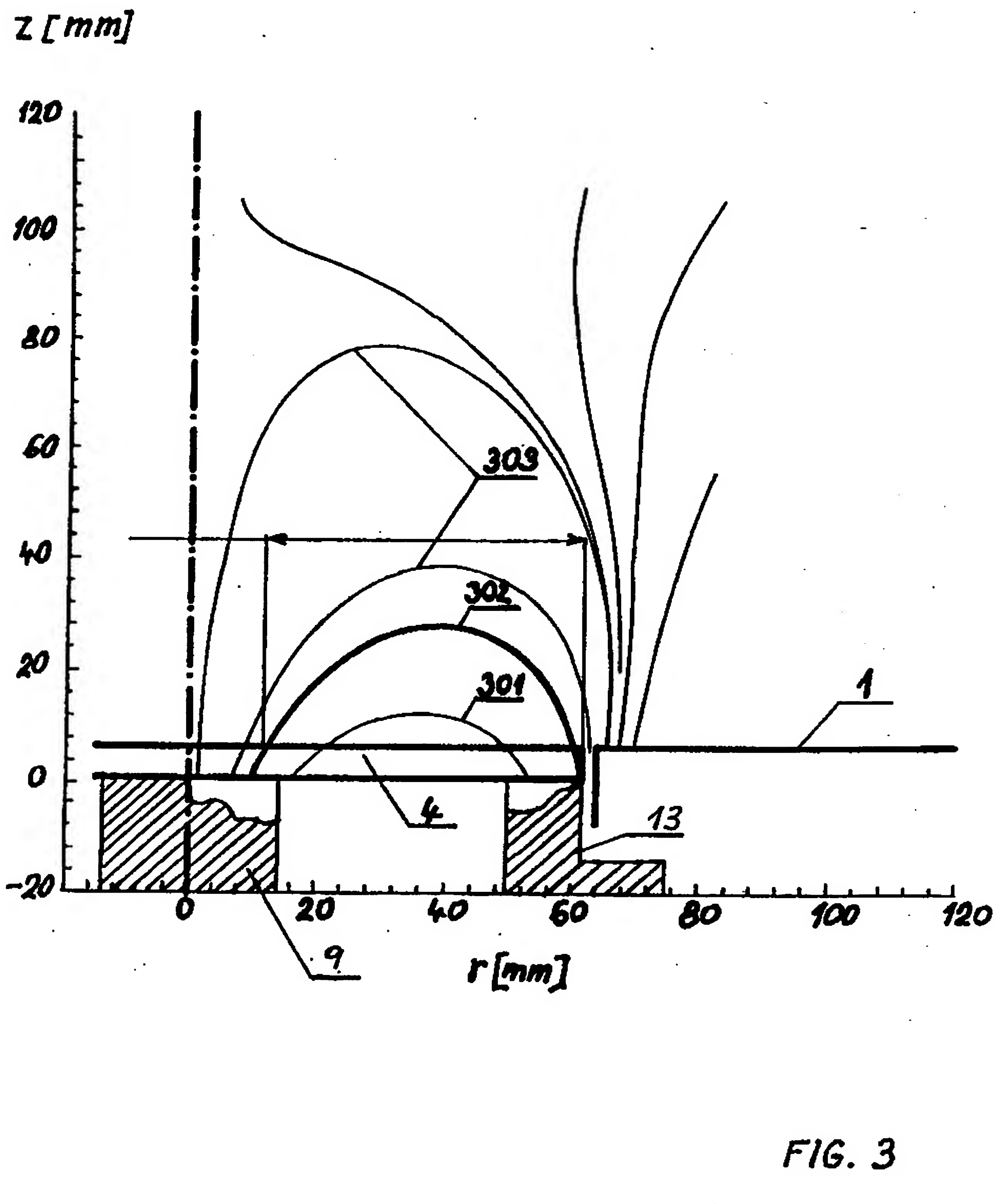
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6
7
8
9
10
l_2/l_1
A
B
C
201
202

FIG. 2


z [mm]
120
100
80
60
40
20
0
-20
303
302
301
1
4
13
9
0
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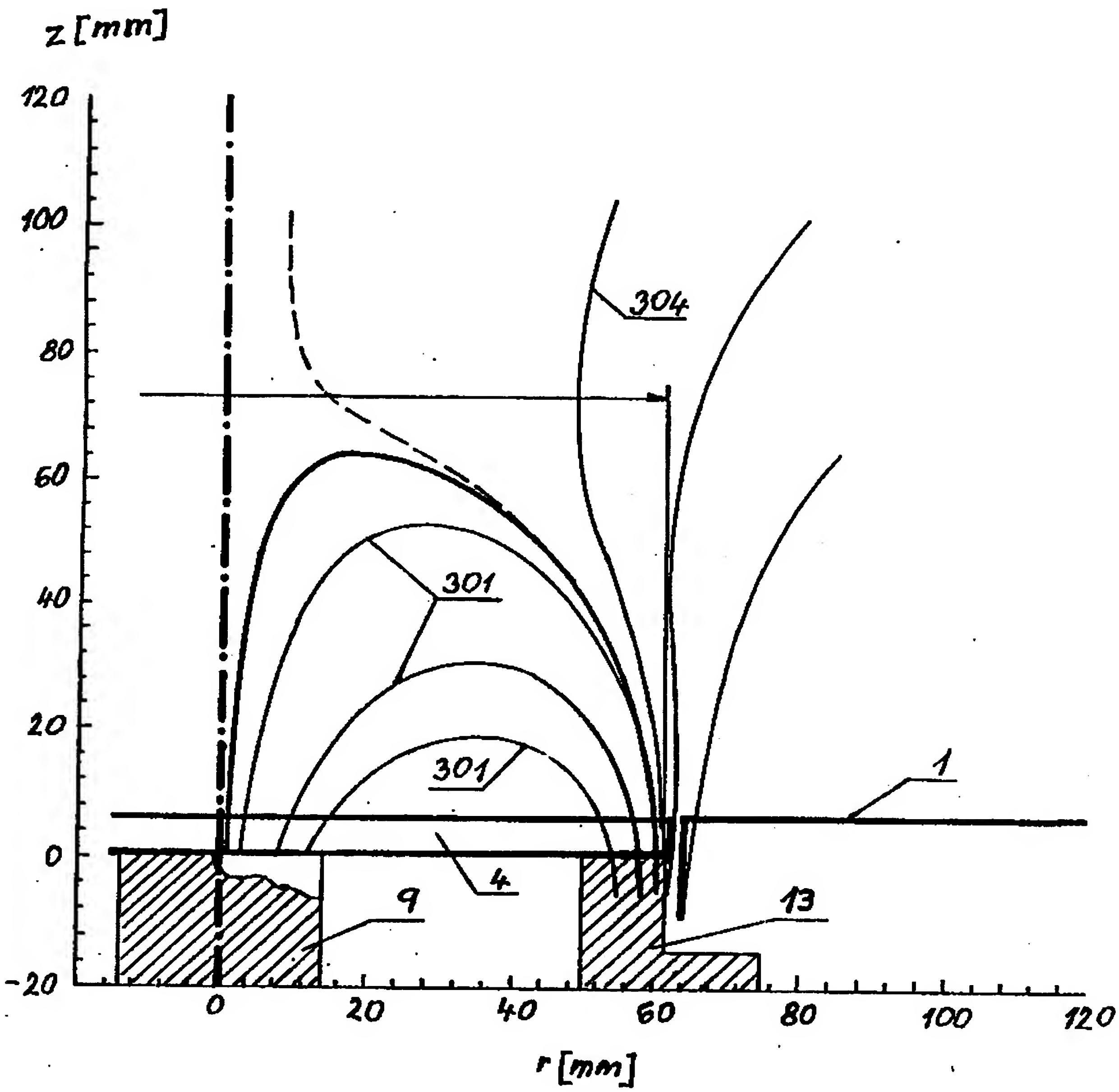
40
60
80
100
120
r [mm]

FIG. 3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80
60
40
20
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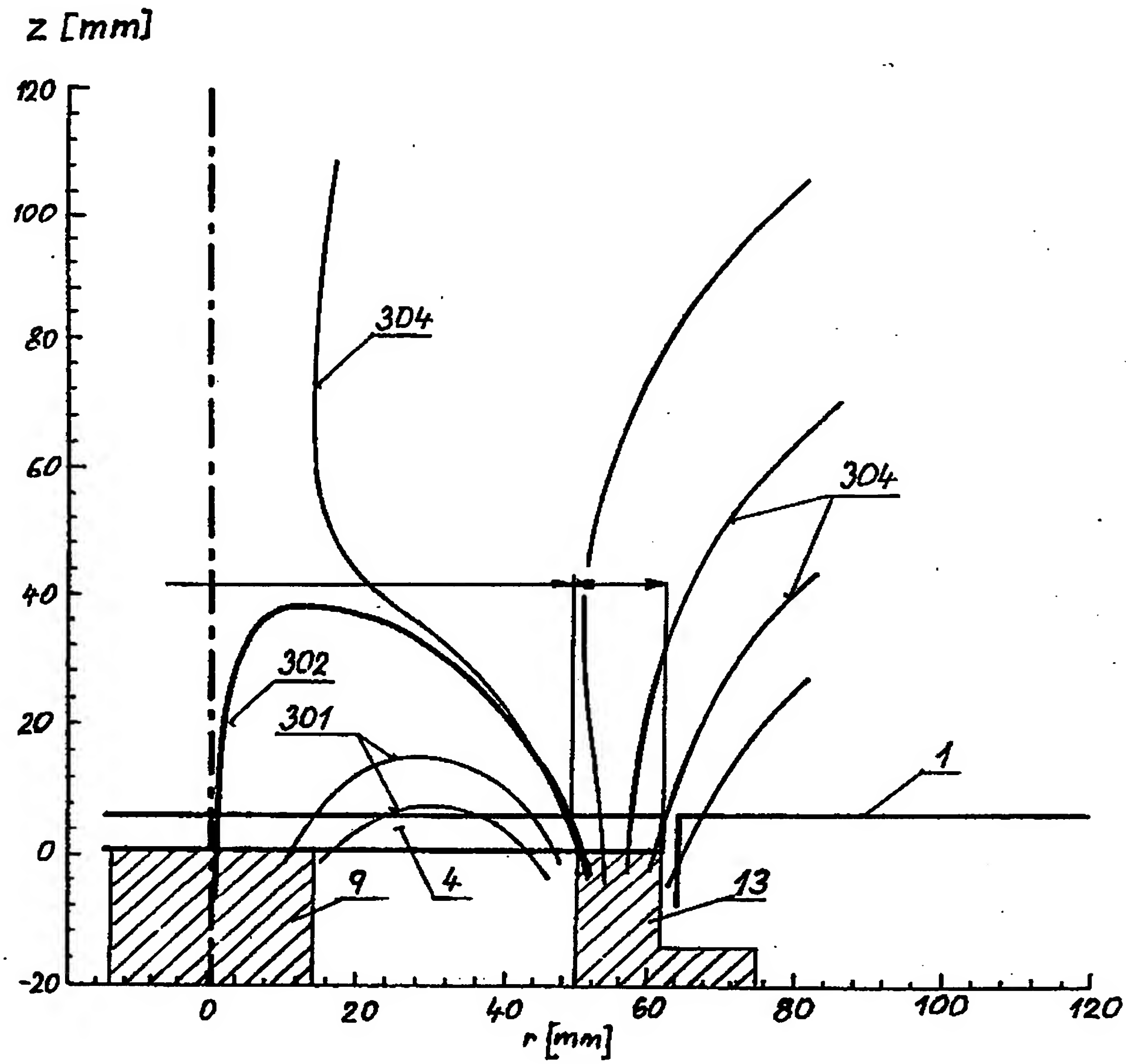
40
60
80
100
120
r [mm]

FIG. 4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80
60
40
20
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60
80
100
120
r [mm]
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304
302
301
1
9
4
13

FIG. 5

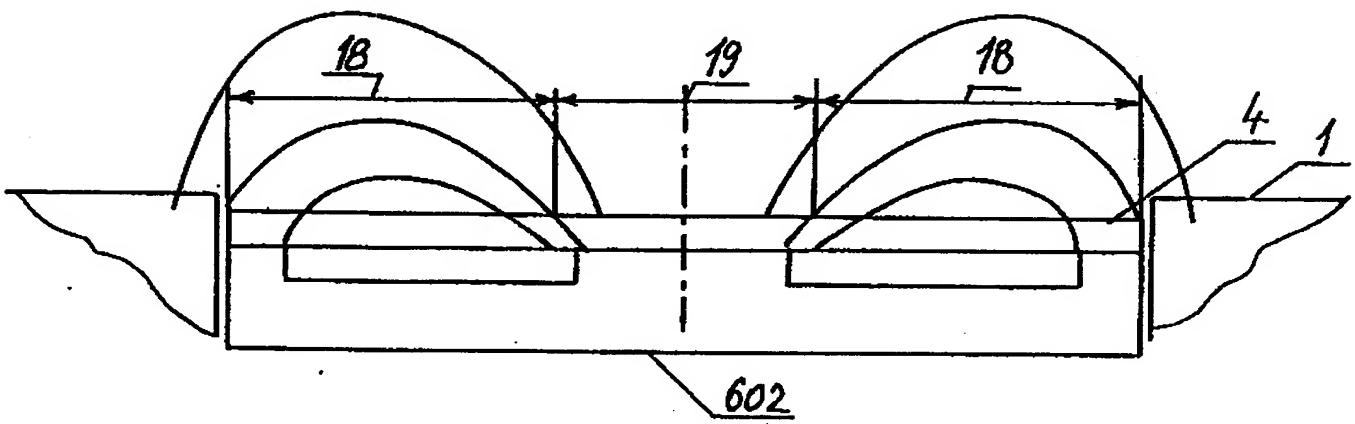


FIG. 6.1

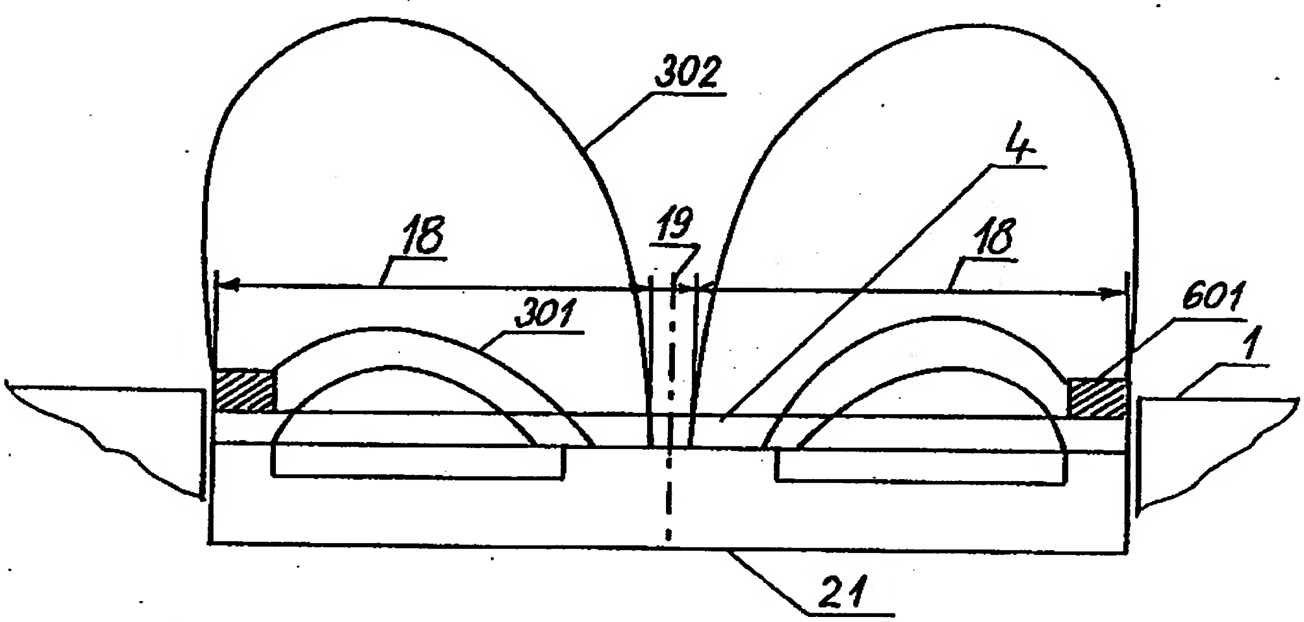


FIG. 6.2

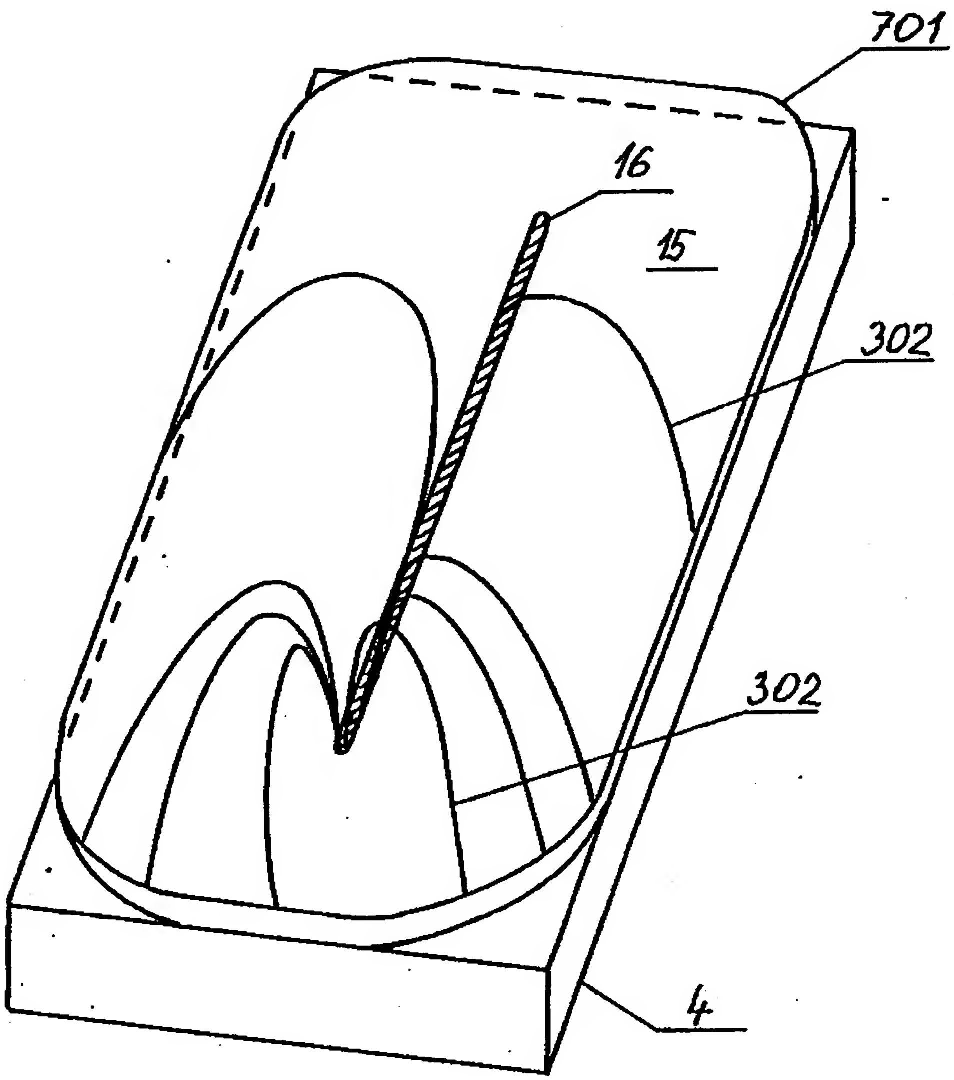


FIG. 7

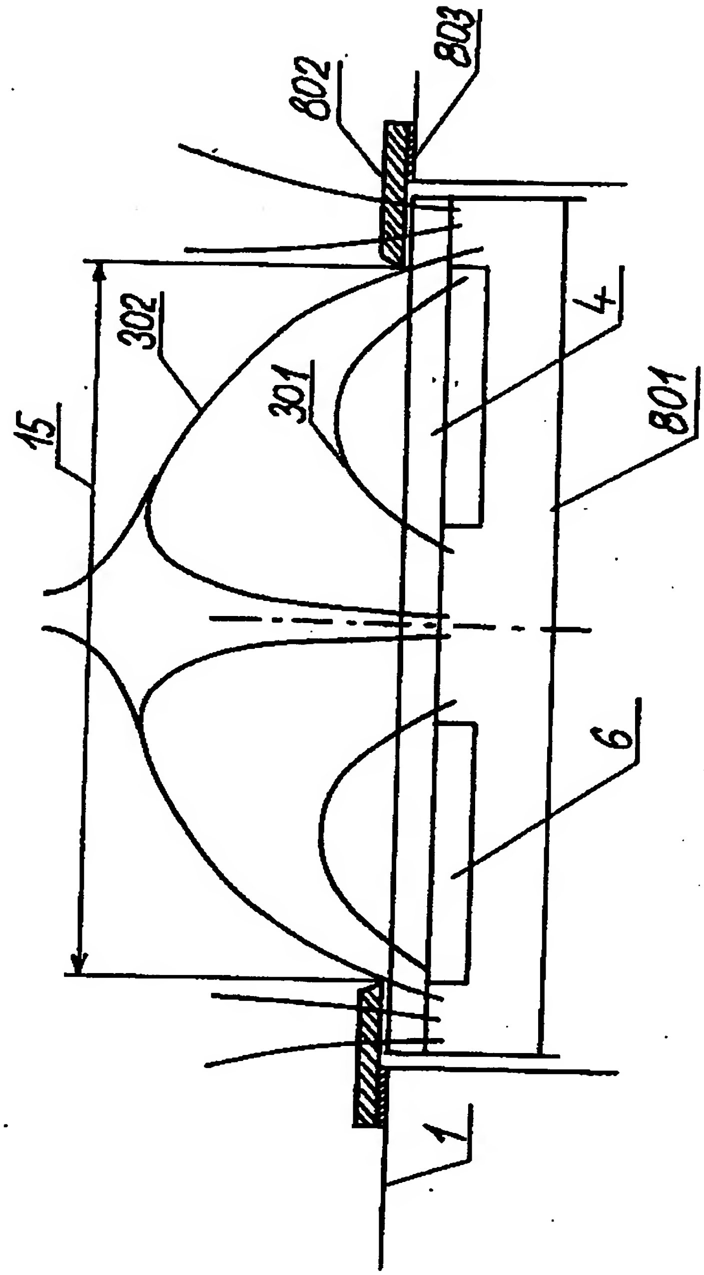
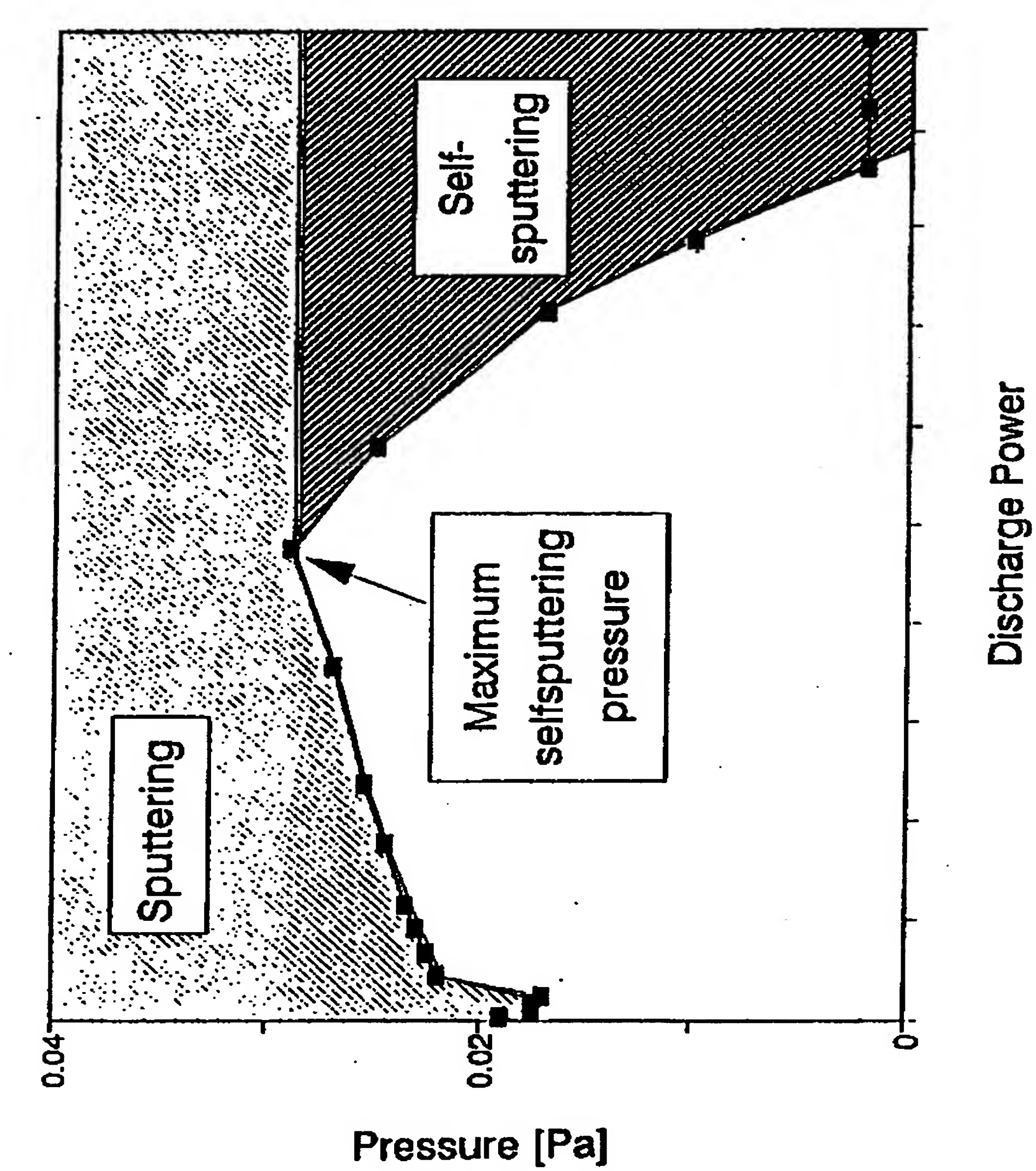


FIG.8


Sputtering
Self-
sputtering
Maximum
selfsputtering
pressure
Discharge Power
Pressure [Pa]
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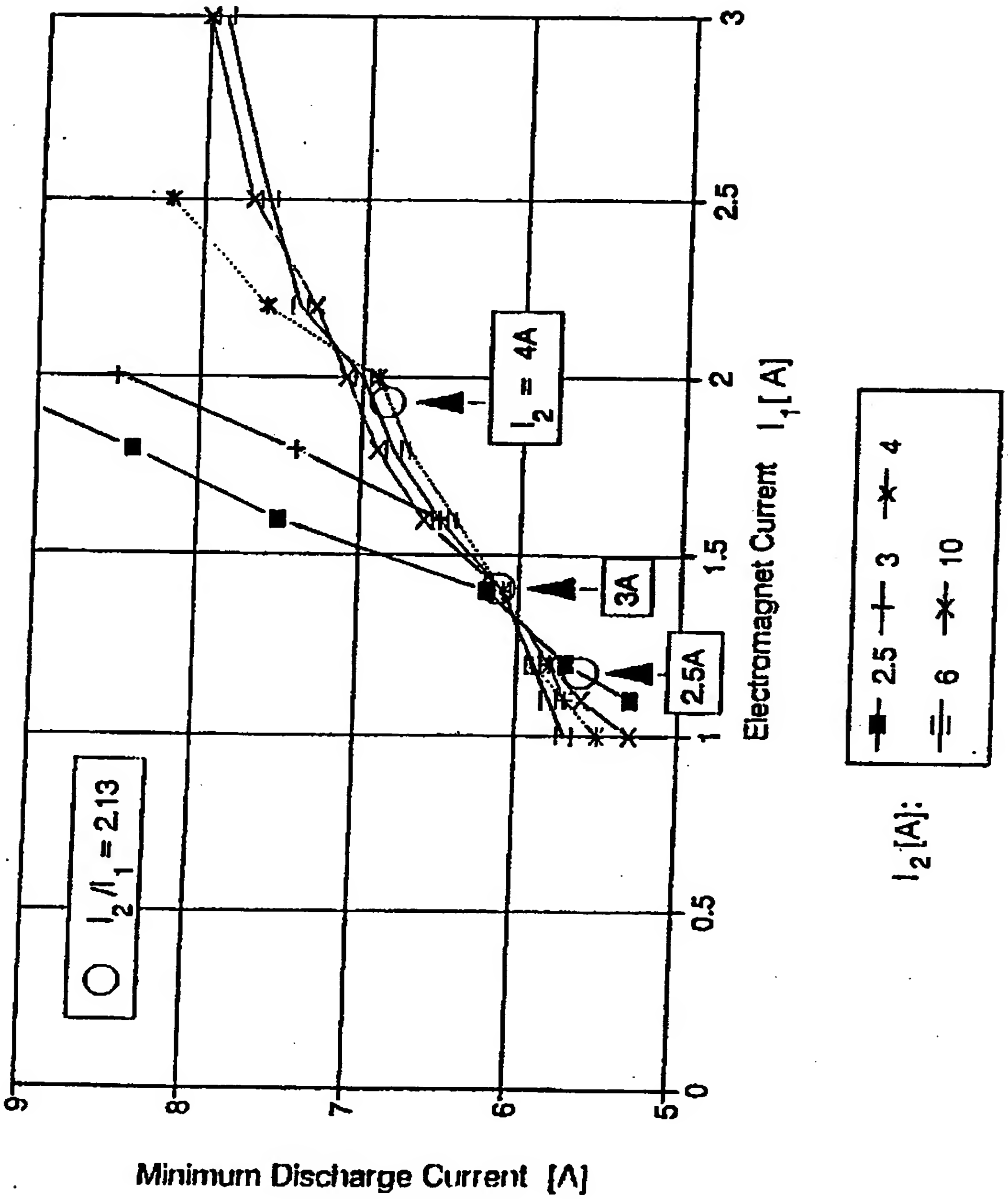
0.02
0

FIG. 9

FIG. 10


Minimum Discharge Current [A]
Electromagnet Current I_1 [A]
$I_2/I_1 = 2.13$
I_2 = 4A
3A
2.5A
I_2 [A]:
2.5
3
4
6
10
9
8
7
6
5
0
0.5
1
1.5
2
2.5
3

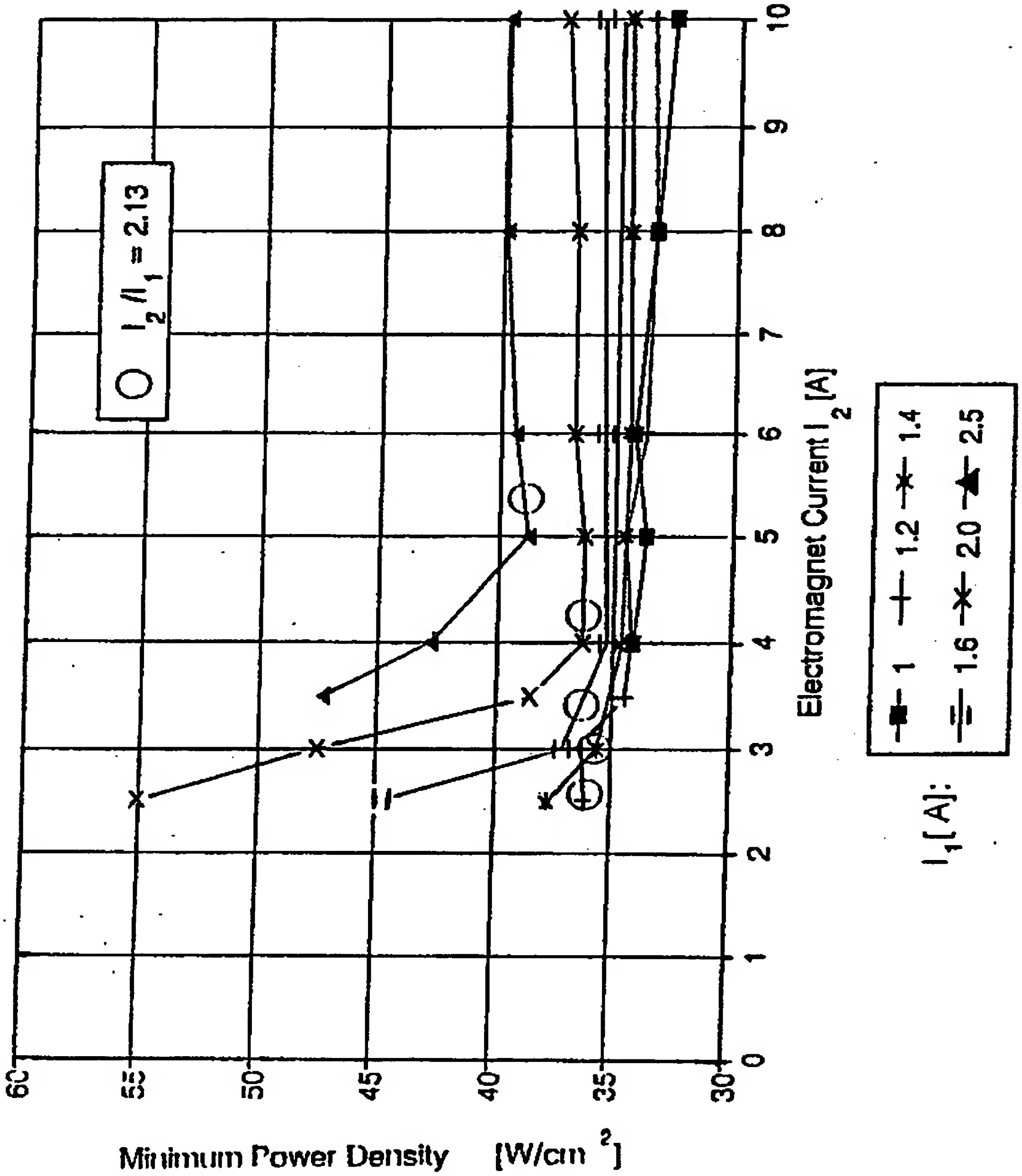
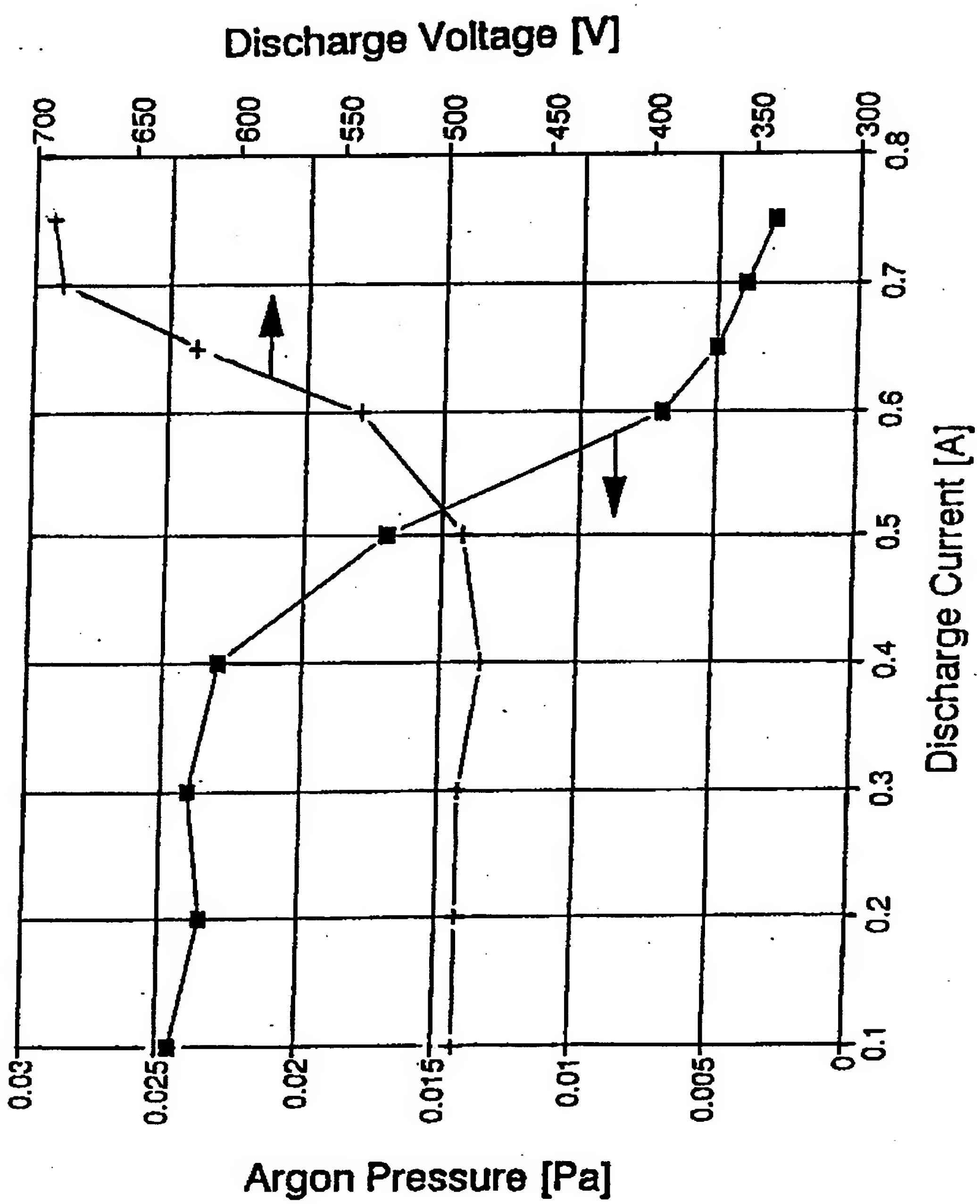

O I_2/I_1 = 2.13
Electromagnet Current I_2 [A]
Minimum Power Density [W/cm²]
I_1 [A]:
1
1.2
1.4
1.6
2.0
2.5
0 1 2 3 4 5 6 7 8 9 10
60 55 50 45 40 35 30

FIG. 11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650
600
550
500
450
400
350
300
Discharge Current [A]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Argon Pressure [Pa]
0.03
0.025
0.02
0.015
0.01
0.005
0

FIG. 12

INTERNATIONAL SEARCH REPORT

Intern. ...nal Application No
PCT/CZ 94/00017

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01J37/34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A,4 865 708 (WELTY) 12 September 1989 see column 9, line 52 - line 68; figures 1,9 ---	1,7, 17-20,24
A	JOURNAL OF VACUUM SCIENCE AND TECHNOLOGY: PART A., vol.10, no.6, November/December 1992, NEW YORK US pages 3430 - 3433 T. ASAMAKI ET AL. 'High-vacuum planar magnetron discharge.' see the whole document ---	1-4,6, 17-19
A	GB,A,2 255 105 (ION COAT LIMITED) 28 October 1992 see page 7, paragraph 2 - page 8, paragraph 1; figure 1 ---	1,17, 22-24
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
28 November 1994	30. 11. 94

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Schaub, G

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INTERNATIONAL SEARCH REPORT

Inter. .onal Application No
PCT/CZ 94/00017

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP,A,0 413 291 (HAUZER HOLDING B.V.) 20 February 1991 cited in the application see abstract; examples -----	1-3

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter. onal Application No
PCT/CZ 94/00017

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
US-A-4865708	12-09-89	CA-A-	2002898	14-05-90
		EP-A-	0442939	28-08-91
		JP-T-	4501585	19-03-92
		WO-A-	9005793	31-05-90
		US-A-	4892633	09-01-90
GB-A-2255105	28-10-92	NONE		
EP-A-0413291	20-02-91	CA-A-	2023092	15-02-91
		JP-A-	3193871	23-08-91
		US-A-	5234560	10-08-93